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ANGULAR WEAVING FOR TURBINE ENGINE COMPOSITE COMPONENTS

Stephen P. Zawislak

Textile Technologies, Inc.
2800 Turnpike Drive
Hatboro PA 19040

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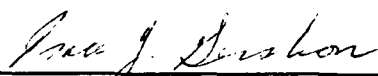
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MICHAEL E. MCINTYRE, SQN LDR, RAF
PROJECT ENGINEER
COMPONENTS BRANCH
TURBINE ENGINE DIVISION


ISAK J. GERSHON
TECHNICAL AREA MANAGER
TURBINE ENGINE DIVISION
AERO PROPULSION & POWER DIRECTORATE

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I. INTRODUCTION

Two dimensional fabrics of woven graphite tows represent the structural backbone of present aerospace composite parts. These fabrics are comprised of 0 and 90 degree systems of yarns, X and Y respectively. They are flat planar structures produced on conventional weaving looms.

Although woven preform designs open a gamut of 0 degree/90 degree fiber orientation options, they do not provide off-axis reinforcement. It was with this in mind that Textile Technologies, Inc. (TTI) actively pursued a solution through the vehicle of this Phase I SBIR (Small Business Innovative Research) project. Entitled "Angular Weaving for Turbine Engine Composite Components", contract F33615-87-C-2793 with the Air Force involved designing and blueprinting a textile machine capable of angular (+/- 45 degrees, 0 degree, 90 degree) weaving to efficiently and cost-effectively fabricate three-dimensional, multi-layer, multi-angular structural composite preforms. For background, this contract followed two previous Phase I contracts: "Assessment of Weaving Techniques for Turbine Engine Components" (Contract #F33615-85-C-2578) and "Assessment of Angular Weaving Techniques for Turbine Engine Composites" (Contract #F33615-86-C-2651), awarded in 1985 and 1986 respectively.

As advanced composite materials find use in more critical aircraft components, many more stringent requirements are placed on reinforcing yarns and fabrics.

Unfortunately, textile loom design has not kept pace with the skyrocketing use of composite materials. In fact, there has never been a loom designed specifically for weaving high modulus (graphite, ceramic, etc.) yarns into fabrics. The entire U.S. composites market is serviced by perhaps 150 looms, not nearly enough potential volume for a commercial textile loom manufacturer to take notice without a guarantee on his initial design investment.

Critical composite parts require precise placement (eg: 0 degree, 90 degree, +45 degree, -45 degree) of high modulus tows (reinforcement member) for optimum strength/weight and modulus/weight ratios. Labor intensive off-axis hand lay-ups can be cited as the industry's primary approach to addressing these needs. In most cases the matrix material provides the only interlaminar strength between plies in such composites. While this approach has been proven structurally satisfactory for most polymer matrix applications, there is a significant need to reduce labor expenses.

Significant to turbine engine composites, matrices such as carbon and ceramic provide very little in the way of interlaminar properties. Angle interlock fabrics (See Figures 1A & 1B) with through-the-thickness yarn reinforcement can address interlaminar property shortcomings in carbon and ceramic matrix composites, but at present that technology cannot offer integral in plane angular woven yarns.

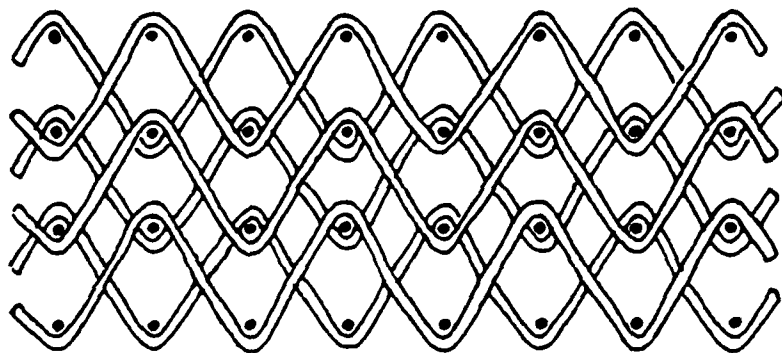


FIGURE 1A - ANGLE INTERLOCK (LAYER-TO-LAYER)

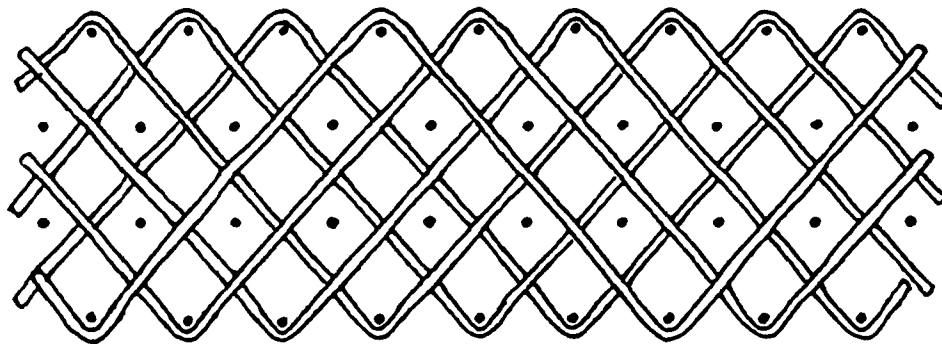


FIGURE 1B - ANGLE INTERLOCK (THROUGH-THE-THICKNESS)

Recent material developmental activities within the aircraft engine industry have stressed the need for near net shape woven preforms for subsequent consolidation into carbon/carbon or ceramic/ceramic parts. The inclusion of off-axis yarns in these parts would add significantly to the success of several current programs involving transatmospheric capabilities.

II. PROGRAM OBJECTIVE

The overall objective of this program was to advance the level of materials and processing techniques for high temperature polymeric, metallic and ceramic matrix composites in order to contribute to improving the performance life, reliability, structural efficiency, and/or to reduce costs of future turbine engines. The major emphasis of this work was directed towards developing a composite reinforcement fabrication system which would address the limitations associated with state-of-the-art techniques. Specifically, TTI and its principal subcontractor have completed a machine design study focused on designing a loom or loom adaptation capable of integrally weaving four (4) or more directions of yarn (multi-angular weaving).

The importance and relevance of this program is probably best summed up in the following quote from TTI's original proposal:

"It is impossible to fully exploit the advantages of dry fabric preforms without the hardware necessary to procure them efficiently. The Air Force is posing very crucial questions related to the performance of materials that do not presently exist. (woven multidirectional fabrics) This program seeks as its ultimate goal, the ability to cost-effectively manufacture these materials."

The capability to weave angular yarns (eg. ± 45 degree) integrally with standard warp (0 degree) and filling (90 degree) yarns would result in composite structures with optimally increased off-axis tensile properties, increased damage tolerance, and higher interlaminar shear strength and rigidity than structures woven without off-axis fiber orientation.

Probably the most significant near-term advantage of this technology in turbine engine composite components would be off-axis reinforcement in integrally woven 3-D angle interlock near net shapes. A leader in the development of this technology, Textile Technologies, Inc. (TTI) has been involved in several multi-layer fabric programs including one with a major aircraft engine manufacturer to integrally weave composite turbine blade preforms. As of the writing of this report, TTI has woven several X, Y, and Z reinforced angle interlock turbine blade preforms. The manufacturer's optimum blade design, however, would include off-axis fiber orientation as the outermost layer of the angle interlock woven blade preform, primarily for torsional rigidity. This requirement fits in well with the present expectations of the loom modifications necessary to weave off-axis yarns, described in detail in this report.

III. PROGRAM REVIEW

Designing a loom capable of integrally weaving four or more directions of yarn is a task never before automated or applied to aerospace grade fiber constructions.

Conventional weaving equipment is designed to handle flexible filaments and yarns for traditional textile uses such as apparel and domestics. "Necessity is the mother of invention", and those markets seldom require quasi-isotropic properties from textiles. Most of the innovations in the field of textiles are brought about in the interest of productivity and design. It is the field of textile design and auxiliary textile motions necessary to facilitate designs which lent themselves to investigation under the confines of this program. In particular, Lappet weaving and its unique methods of manipulating auxiliary warp yarns became the basis from which to build our investigation.

Historically, lappet weaving was first engineered to weave the fashionable "paisley" shawl and was employed for manufacturing intricate designs in lace, draperies, and upholstery materials. In most cases, lappet weaving has been replaced by more efficient fabrication techniques. In fact, at present there are only two active lappet weaving mills in the world. Both these mills are located in the United Kingdom, one in England, the other in Scotland. Both mills enjoy flourishing businesses weaving planar cloth of exotic embroidered surfaces for traditional head wrappings for primarily Middle-Eastern markets.

A. PRIME SUBCONTRACTOR

Mr. Paul Wagner, President of Henry Riehl, Incorporated was the prime subcontractor on this program specializing in mechanical adaptability of design concepts and mechanical drawing.

Mr. Wagner is the chief machinery designer and builder at one of this country's most respected specialty textile machine shops. Henry Riehl, Inc. has been instrumental in building many of the narrow fabric batten looms utilized today by many of the suppliers to the aerospace industry. Henry Riehl, Inc. specializes in total loom conversions, many times utilizing unique parts designed and manufactured in-house.

B. PROGRAM ACTIVITIES

In this text, program activities are reported in the same format as the Phase I work plan outlined in TTI's original proposal. That format is as follows:

TASK 1: Background Literature Search

TASK 2: Data Analysis

TASK 3: Formulate Machine Design

TASK 4: Develop Blueprint of Design

TASK 5: Forecast/Assess the Capability of the New Loom Design

TASK 6: Reporting

TASK 1: BACKGROUND LITERATURE SEARCH

The objective of this task was to concentrate on detailed investigation of mechanical fabrication techniques, past and present, applicable to the design of a new angular weaving machine. Particular emphasis was placed on certain mechanical motions inherent to lappet weaving which could prove useful in manipulating auxiliary warp systems into angular woven yarns.

Following is a list of institutions and trade shows visited/attended for the purpose of information and knowledge pertinent to the success of this program.

<u>INSTITUTION/EVENT</u>	<u>RELEVANCE</u>
Philadelphia College of Textiles & Science	Reference books and periodicals for background on past and present textile fabrication techniques. Of particular interest were reference texts on lappet weaving found in the PCT & S archives.
Scottish College of Textiles	Verbal communications relevant to lappet weaving and the existence of operating lappet looms.
Pennsylvania Historical & Museum Commission	Reference books on antiquated textile weaving techniques.
Smithsonian Institute (American Textile Museum)	Reference books on antiquated textile weaving techniques.
University of Lowell, MA	Verbal communications relevant to lappet weaving in America (extinct)
National Trust Show Washington, DC	Attended this show to establish whereabouts of existing lappet weavers.
ITMA, '87 Paris, France	World's largest exhibition of textile machinery. Valuable in assessing existing techniques of yarn manipulation. (Discussed in further detail in this report.)

Of all the sources listed, the most significant literature gains were found in exploring the archives of the Philadelphia College of Textiles and Science, and at the American Textile Museum of the Smithsonian Institute. In particular, publications critical to the understanding of lappet technology were pulled from shelves and dusted off.

The age of most of the publications coincided with the apparent heyday of lappet weaving 1830-1900. In the absence of viewing an actual lappet loom, these publications offered detailed schematics of the individual moving parts of the lappet loom.

Aside from the obvious benefits gained by locating the mechanical schematics of the lappet weaving motion, it soon became apparent that witnessing the mechanical operation of a working lappet loom would be an immeasurable advantage in designing the target angular weaving machine. As a result, Textile Technologies, Inc. concentrated on locating and accessing an actual working loom.

Contacts initiated at the National Trust Show and with the Scottish College of Textiles in Edinburgh, Scotland, were instrumental in locating two textile manufacturers with lappet looms, both of which operate within the United Kingdom. The manufacturer located in Scotland was extremely helpful and cooperative, and agreed to a meeting.

On 16 October 1987, Stephen P. Zawislak, the principal investigator, met with two technical engineers from Loudoun Valley Manufacturing Company, Scotland, at the 1987 ITMA Exhibition in Paris, France.

After outlining Textile Technologies, Inc.'s basic intentions, Loudoun agreed to allow Stephen Zawislak to visit their mill, and discuss basic research intentions.

The meeting occurred on 20 October 1987, and Loudoun proved to be very cooperative and interested in supporting any efforts Textile Technologies, Inc. (TTI) may decide to pursue regarding graphite weaving on lappet or "modified lappet" looms. The following events occurred during that meeting:

1. The principal investigator viewed a late model lappet loom with three guide bars operating from the top side of the foundation warp threads.
2. The principal investigator, with Loudoun engineers, performed basic trials successfully on their equipment to make lappet yarns move at a desired angle.
3. The basics of our research approach were outlined for feedback on practicality of design and producibility. Loudoun adapts their own machines and felt the primary concept was workable.

Prior to visiting Loudoun Valley Manufacturing Company, the principal investigator attended ITMA, '87 in Paris, France. ITMA, '87 was the largest collection of textile machinery ever arranged.

The primary motive for attending this show was to evaluate commercial mechanical motions available for manipulating yarns and how they may be applicable to the design work in this program. The most significant applicable developments were as follows:

1. Liba Copcentra Multi-Axial Machine: Witnessed videotape viewing of machine in action.

2. Mayer Multi-Axial Warp Knitting Machine: Actual machine demonstration. Interest in yarn guides and rotating warp.
3. Specific machine parts of both Mayer and Liba Warp Knitting Machines:
 - eg) Pattern Chain - possible adaptation to angular weaving concept.
4. Computer Aided Patterning System:
 - eg) Bonas, U.K. - possible need if mechanics become cumbersome in machine design.
5. Possible application of needle loom mechanics.
6. Knitting needle concepts for yarn guides - potential yarn abrasion point.
7. Unique reed arrangements.

TASK 2: DATA ANALYSIS

2a. ALTERNATE CONCEPTS

Although lappet weaving formed the basis of our research from the very beginning, it was deemed necessary to investigate several alternative design concepts for weaving multiangular fabric. Three of those concepts are outlined briefly below.

- 1.) Triaxial weaving is a technique developed in the late 1960's which can provide off-axis fiber orientation in a 2-D fabric structure. Two warp yarn systems are woven ± 30 degrees to the filling yarn. (See Figure 2)

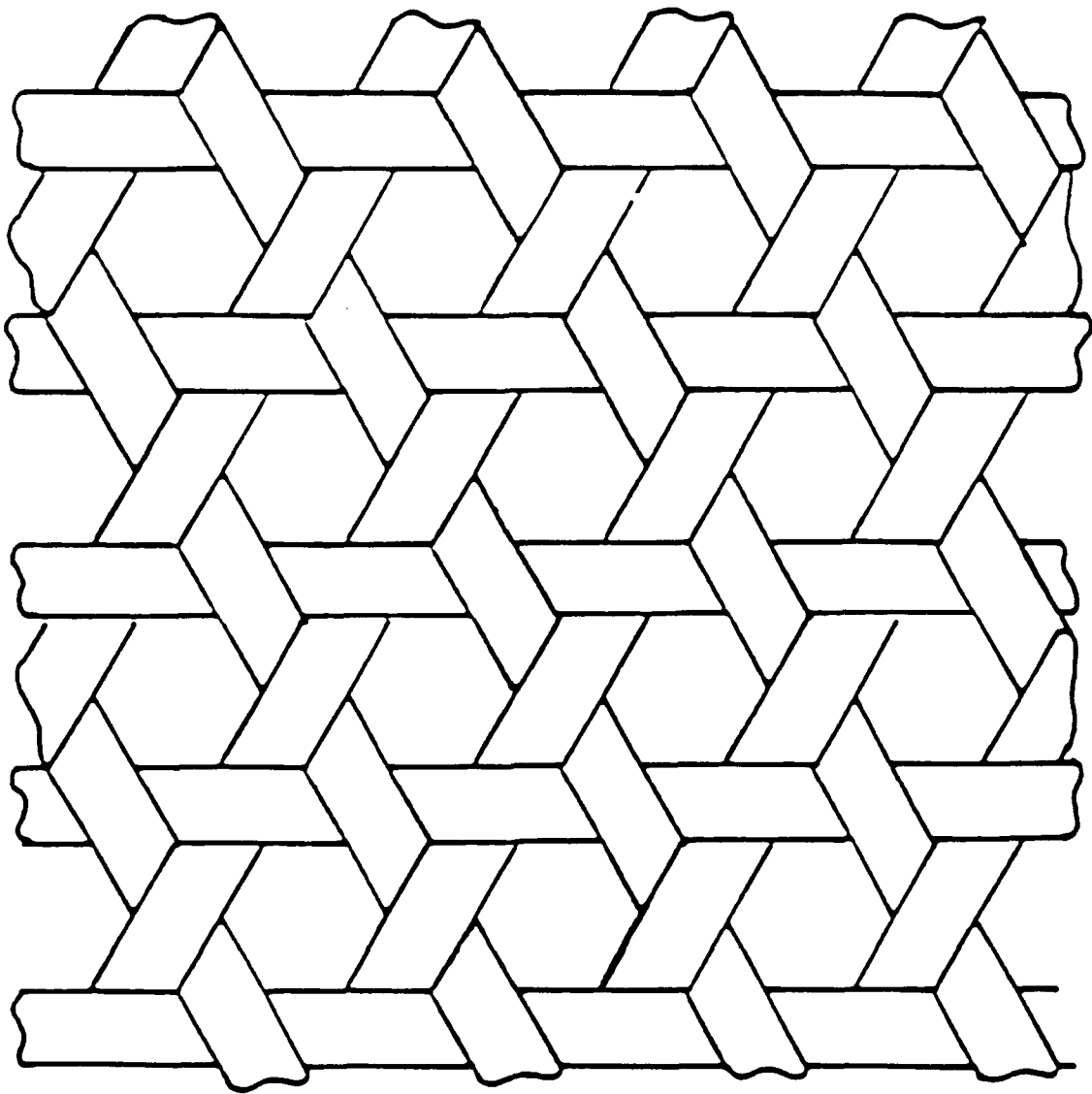


FIGURE 2 - TRIAXIAL WOVEN FABRIC CONSTRUCTION

Several limitations exist when comparing this technology to the needs of the aerospace industry. First, present machinery design has not proven efficient in converting aerospace grade fibers into fabric form. Significant fiber damage has been demonstrated. Second, available weave designs exhibit characteristic porosity in the form of evenly spaced hexagonal holes, ideal for acoustic applications, but detrimental in attaining target fiber volumes and avoiding resin pockets in aerospace composites. Third, commercial equipment is scarce with most looms out of action for the past several years. Fourth, there has been no work performed on the applicability of this technique to structural shapes.

2.) At present, standard broadloom graphite weaving is done on rigid rapier looms such as those manufactured by IWER and DORNIER. (See Figure 3) Rigid rapier filling insertion is preferred due to the gentle motion of the insertion rapier. A filling yarn may be inserted with little or no abrasion to the warp yarns resulting from the pick insertion.

Since this method is a proven technique for weaving high modulus yarns, TTI and its principal subcontractor investigated possible applications to multi-angular weaving. As illustrated in Figure 4, conceptually three rigid rapiers would be required to insert three separate filling yarns across the same 0 degree warp. If this concept were to be advanced further in design, at least several mechanical hurdles would have needed attention.

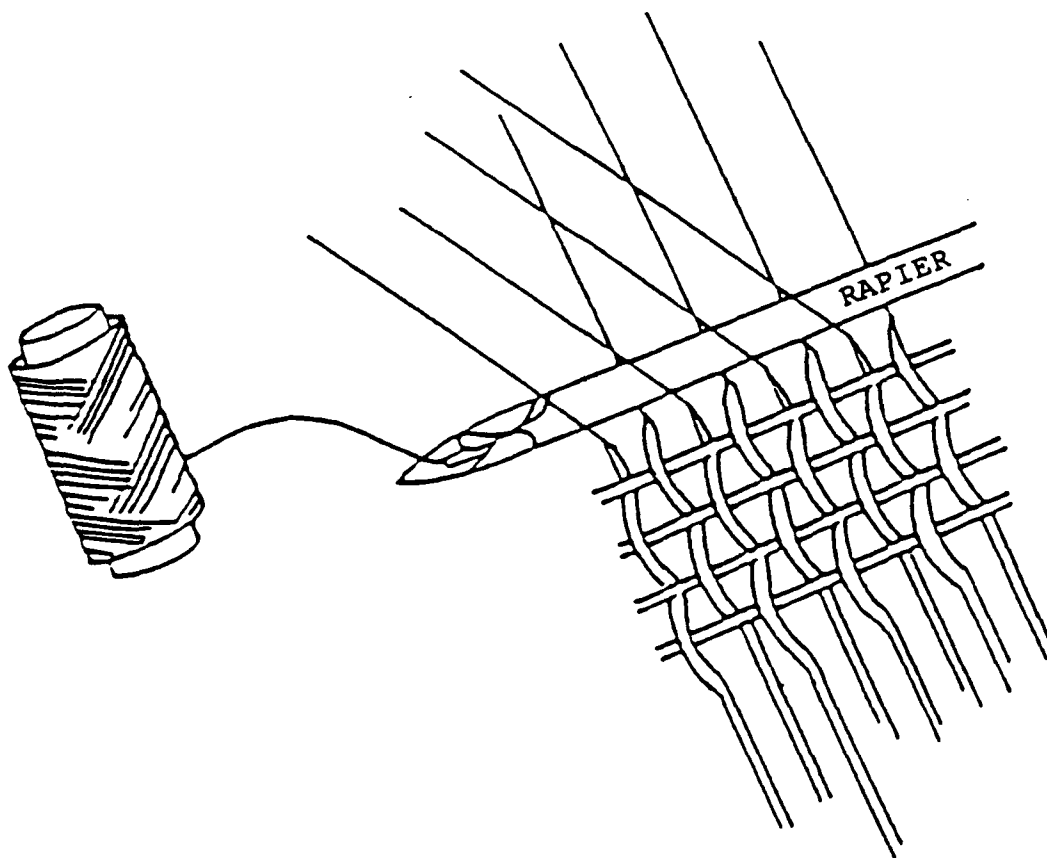


FIGURE 3 - RIGID RAPIER FILLING YARN INSERTION

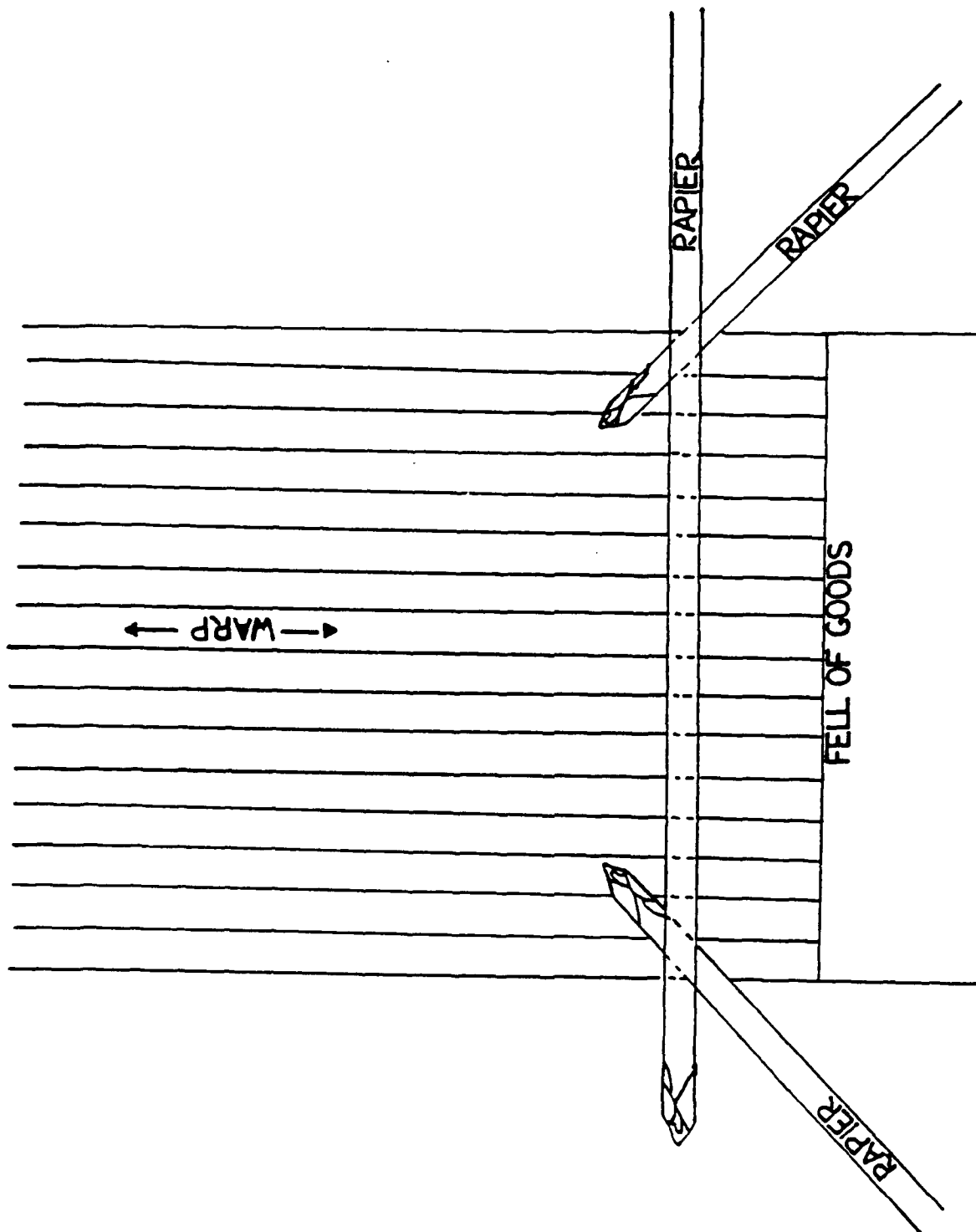


FIGURE 4 - ALTERNATE CONCEPT, ANGULAR YARNS WOVEN VIA RIGID
RAPIER INSERTION

a.) Both perpendicular and angular warp sheds would need to be opened for insertion of all three filling yarns. This would require either several dobby arrangements (weave patterning device) specific to the required woven angle, or possibly a modified jacquard arrangement (weave patterning device).

b.) Beat up of the inserted filling yarns at various angles to the longitudinal warp would require twin swinging single sided reed arrangements for each rigid rapier angle.

c.) In most loom designs, space is of a premium; a completely new loom frame design would be required to accommodate two additional filling insertion mechanisms.

Work on this design concept ceased primarily due to a limitation of all rapier looms. The fact that the filling yarn is drawn across the warp from a filling yarn package on one side of the warp necessitates that each filling yarn be cut before the rapier is free to advance another filling yarn into position. As such is the case, this weaving technique would be limited to flat fabric constructions, thus not addressing the Air Force need for multi-angular multi-layer woven shapes. Woven shapes can only be realized by weaving with a shuttle. (See Figure 5) A shuttle is a filling yarn insertion vehicle which houses the filling yarn package thereby weaving the looped edge necessary in weaving shapes.

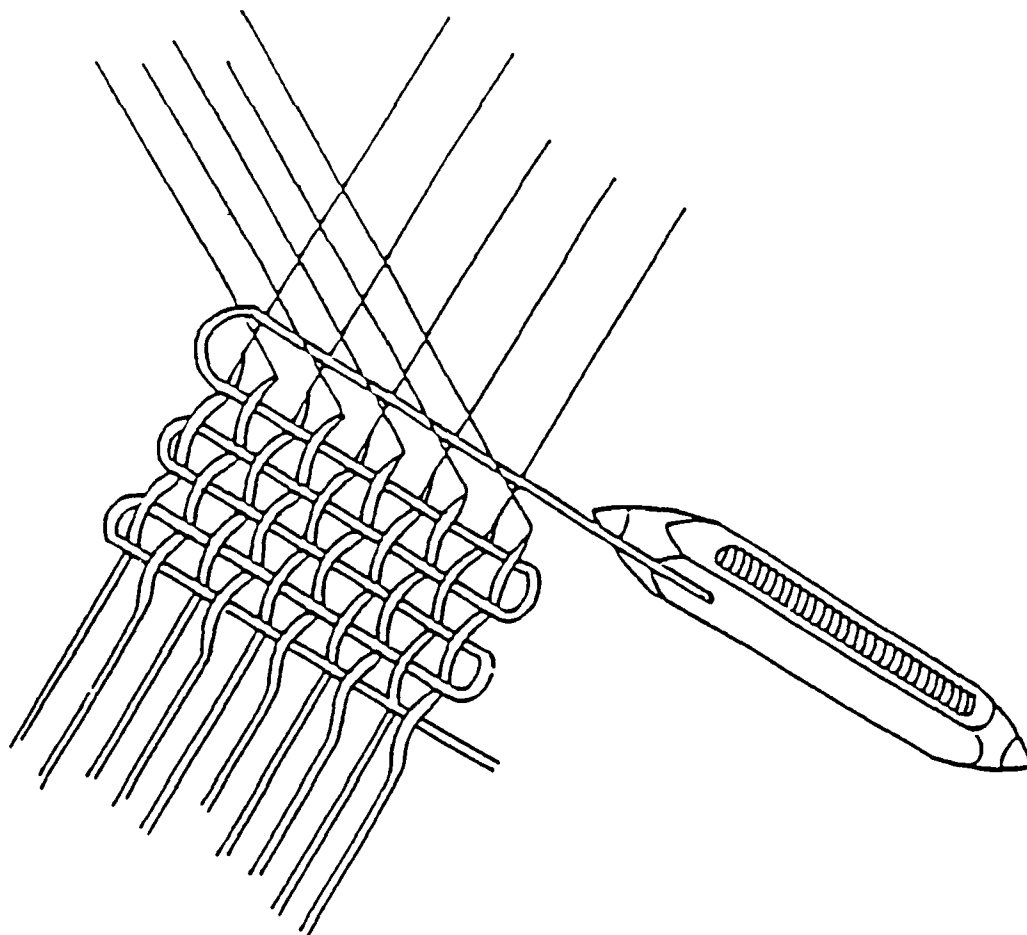


FIGURE 5 - SHUTTLE FILLING YARN INSERTION

3.) Projectile weaving, that is the filling insertion technique common to looms such as the Sulzer is a weaving method which inserts a filling yarn across a weaving shed by attachment of the filling yarn to a flying projectile. At the completion of the weaving motion (shed closes and reed beats up), the projectile releases the filling yarn and is transferred via conveyor back to its original position and reloaded into the firing mechanism for insertion of another filling yarn. Several projectiles are used in sequence.

For purposes of weaving multi-angular fabric, it was conceived that the "projectile" described earlier be replaced by a down-sized shuttle (inclusive of filling yarn package). Then, at the completion of the weaving motion (after the filling yarn is inserted), the trailing yarn from the last shuttle fired could be picked up by a yarn guide traveling in the opposite direction of the inserted filling yarn. It is proposed that the filling yarn guides could be incrementally raised-lowered-indexed in the same fashion as the needle heddles proposed for the modified lappet technique (primary concept described later in this report). Accommodations would need to be made to transfer the shuttle(s) in the direction of the moving filling yarn guide(s).

Assuming that filling shuttles can be fired from both sides of the woven cloth, the resultant yarn patterns within the conceived fabric construction would be as in Figure 6.

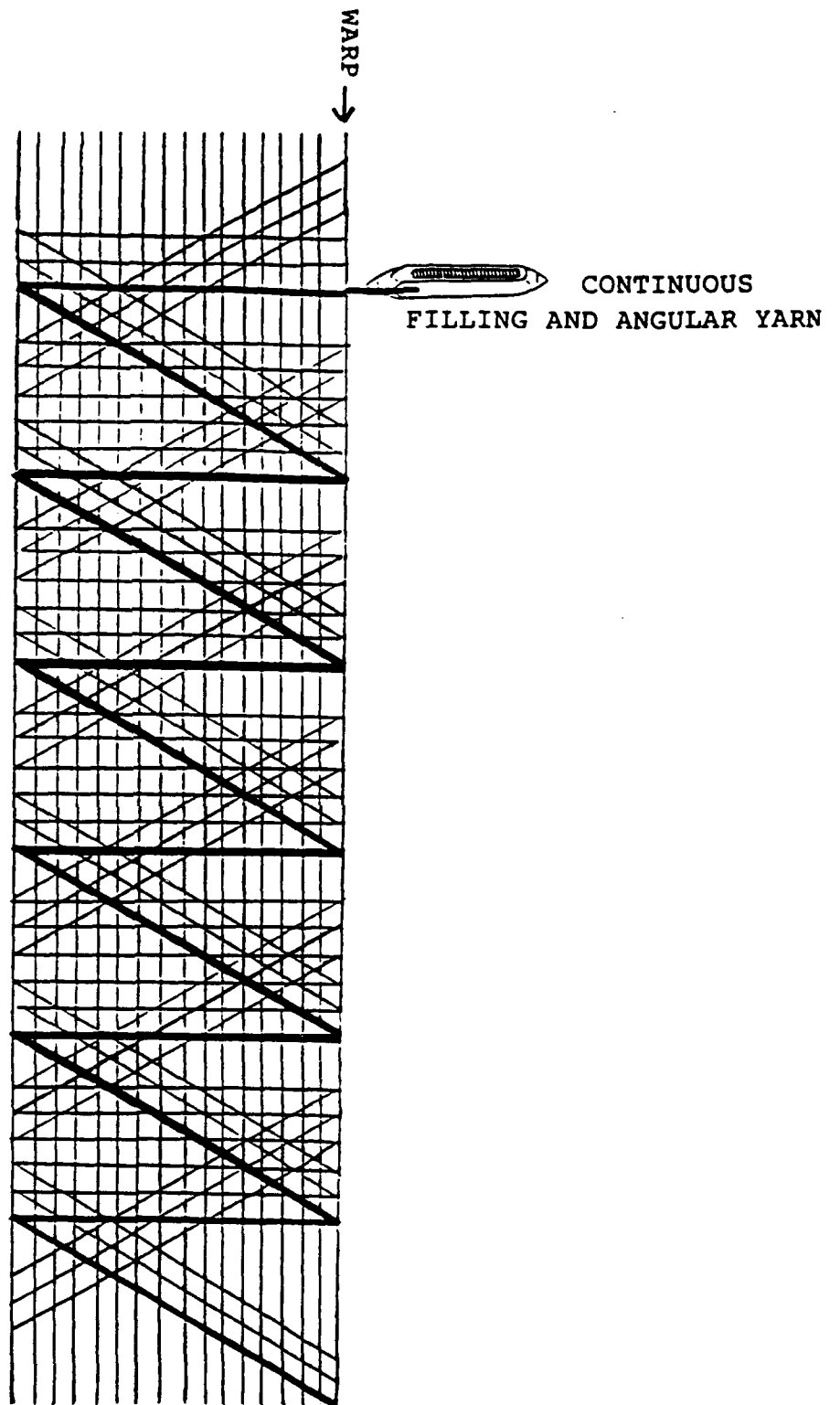


FIGURE 6 - ALTERNATE CONCEPT, ANGULAR YARNS WOVEN VIA
PROJECTILE/MODIFIED LAPPET WEAVING

This proposed technique for angular weaving offers two (2) very important advantages over the other techniques described in this report, the "angular woven yarns" are self-contained (within a shuttle) and are attained via a filling yarn technique versus a warp yarn technique.

The apparent disadvantages, however, outweighed the advantages in the opinion of the development team. The following reasons are offered:

- a.) Weaving with a flying shuttle is generally considered inadvisable with high modulus yarns.
- b.) Space around the weaving area of the loom would no doubt be cramped having to accomodate two shuttle firing devices, two needle heddle tracks, and some mechanism devised to accomodate the shuttles.
- c.) A completely new shuttle design would be necessary.
- d.) The conceived weaving technique would require a total loom design rather than a loom conversion. The development team has only limited experience with projectile looms.
- e.) Difficulties are foreseen in weaving shapes with this technique, thus not addressing Air Force requirements.

2b. PRIMARY CONCEPT - MODIFIED LAPPET WEAVING

As stated previously, Lappet weaving is the basis upon which our primary design concept for a multi-angular weaving machine is based. More specifically, the mechanics of moving auxiliary warp (lappet) yarns relative to a foundation warp was of prime interest.

To better understand the proposed concept, it is important to understand lappet weaving as it is presently performed.

Lappet weaving is a system of weaving, the unique features of which are illustrated in Figures 7A and 7B, whereby figuring yarns are introduced as additional warp on a foundation fabric. In the process of forming the design, the additional warp yarns are traversed in a horizontal direction on the face side of the cloth, and are bound to the foundation fabric by the insertion of a filling yarn at the extremity of each traverse. Figure 8 shows a schematic of the basic motions involved in lappet weaving. Important aspects of the lappet patterning mechanism include the following:

- 1.) The figuring yarns are guided laterally on fixed guide bars; the "practical" range of lateral motion being approximately one inch.
- 2.) The guide bars are controlled via a cam system.
- 3.) The pattern guides on the guide bars must move vertically through the foundation warp sheet and a filling yarn must be inserted for the figure yarn to be bound to the foundation fabric.
- 4.) The vertical motion of the pattern guides through the foundation warp sheet must occur with the reed in the rear (open shed) position to allow for insertion of the filling yarn.

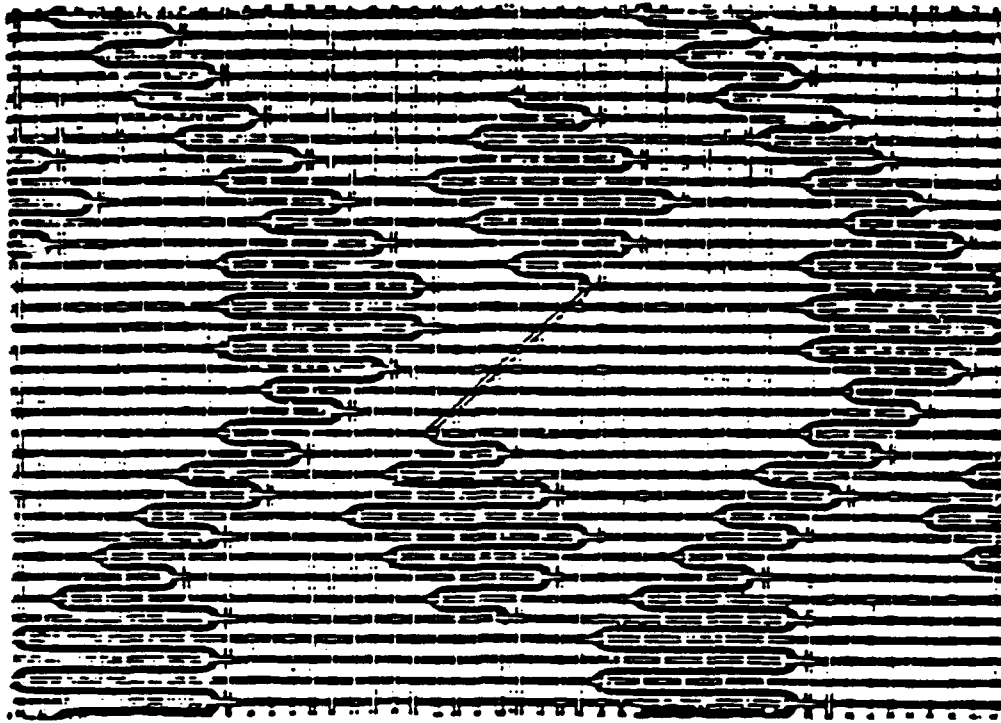


FIGURE 7A - SCHEMATIC OF LAPPET FABRIC

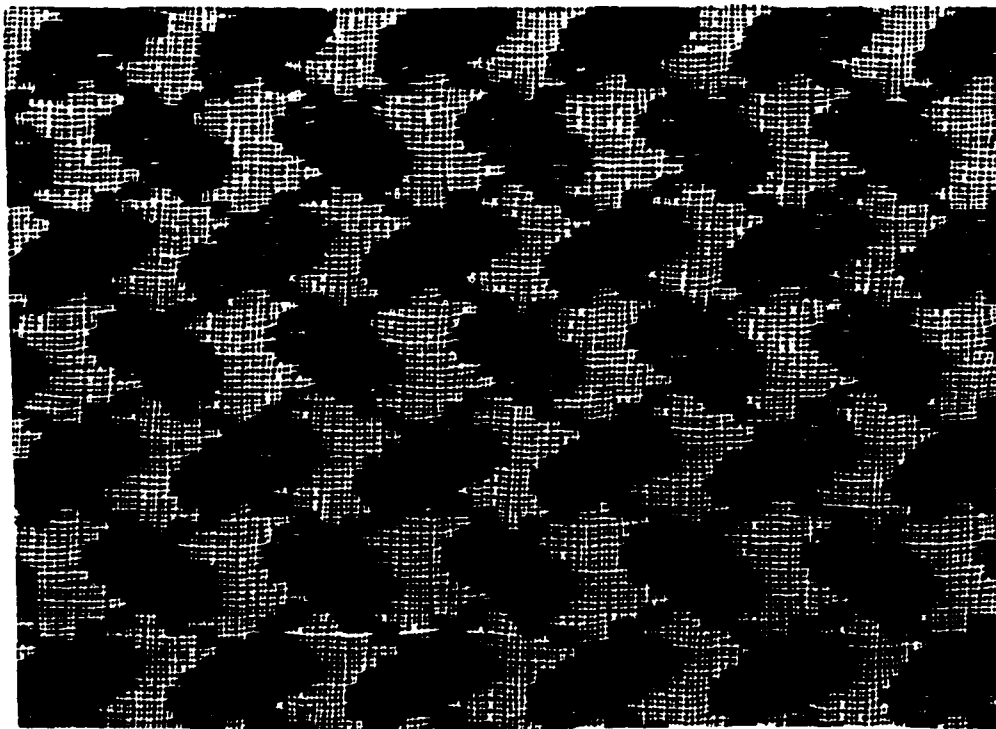
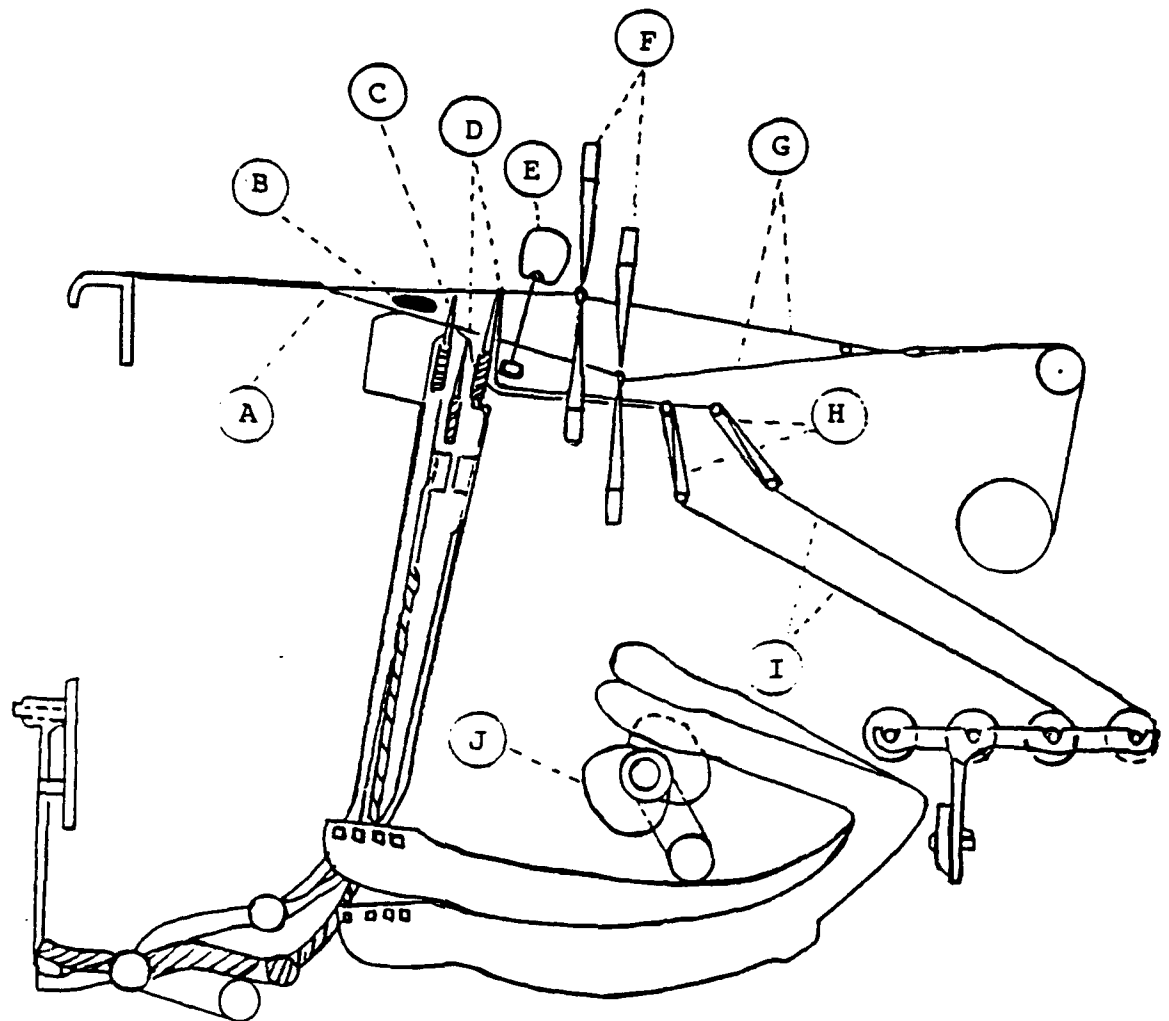


FIGURE 7B - TYPICAL LAPPET FABRIC FOR MID-EASTERN
HEAD WRAPPINGS



- A. FELL OF THE WOVEN CLOTH
- B. SHUTTLE
- C. FALSE REED
- D. LAPPET GUIDE BARS
- E. TRUE REED
- F. HARNESSES
- G. FOUNDATION WARP
- H. TENSION DEVICE FOR LAPPET WARP
- I. LAPPET (FIGURING) WARP
- J. CAM MOTION FOR VERTICAL MOTION OF GUIDE BARS

FIGURE 8 - LAPPET LOOM SCHEMATIC (SIDE VIEW)

5.) The pattern guides must move vertically away from the foundation warp sheet for the reed to beat-up the inserted filling into the fell of the foundation fabric, thus binding the figuring yarn to the foundation fabric.

TASK 3: FORMULATE MACHINE DESIGN (PRIMARY CONCEPT)

While conceiving a new machine design, of primary concern are various mechanical details. But it is just as important to keep in mind the desired form of the final woven product. For this reason, a small fabric model was hand-woven from multicolor synthetic yarns to visualize a single layer of multidirectional (0, 90, +45, -45 degree) woven fabric. Mr. Paul Wagner of Henry Riehl, Incorporated also constructed a pair of pattern guide bars to mimic the lappet weaving technique on a small hand loom.

This technique assisted the primary investigators in establishing potential limitations associated with certain mechanical approaches.

The joint approach of TTI and Henry Riehl, Incorporated was to adapt the basic mechanical motions associated with lappet weaving for angular movements of the "figuring yarns" (auxiliary warp). As previously stated, the "figuring yarns" in lappet weaving are guided laterally on fixed guide bars with limited range of motion.

With respect to the lappet technique, the limiting factor prohibiting full angular range of the "figuring yarn" from selvage to selvage is the length of the fixed guide bars, and the subsequent covering of the full fabric width with the figuring yarns. To eliminate this limitation, it was decided that a bed of individual sequential "figuring yarns" (angular warp) guides or needle heddles (See Figure 9) should replace the fixed guide bars of the lappet technique. To further digress from the original lappet concept, the individual needle heddles should index in a closed loop clockwise rotation. Continuous clockwise rotation of the needle heddles will eventually yield a continuous angular warp pattern as illustrated in Figure 10. With the inclusion of the rotating needle heddles in place of the fixed guide bars of the lappet technique, the basic filling yarn insertion technique is as follows: (NOTE: Ref. Blueprint 02 - Proposed Idea for Angular Weaving - Perspective View)

1.) In the presence of an open shed, selected needle heddles move vertically (from above or below fabric) through the foundation warp sheet to the opposite side of the split warp shed.

A filling yarn must be inserted for the angular warp yarn to be bound to the foundation fabric.

2.) Individual needle heddles may be selectively raised or lowered by a jacquard mechanism thus binding the angular warp yarns to the foundation fabric in a fully controlled manner.

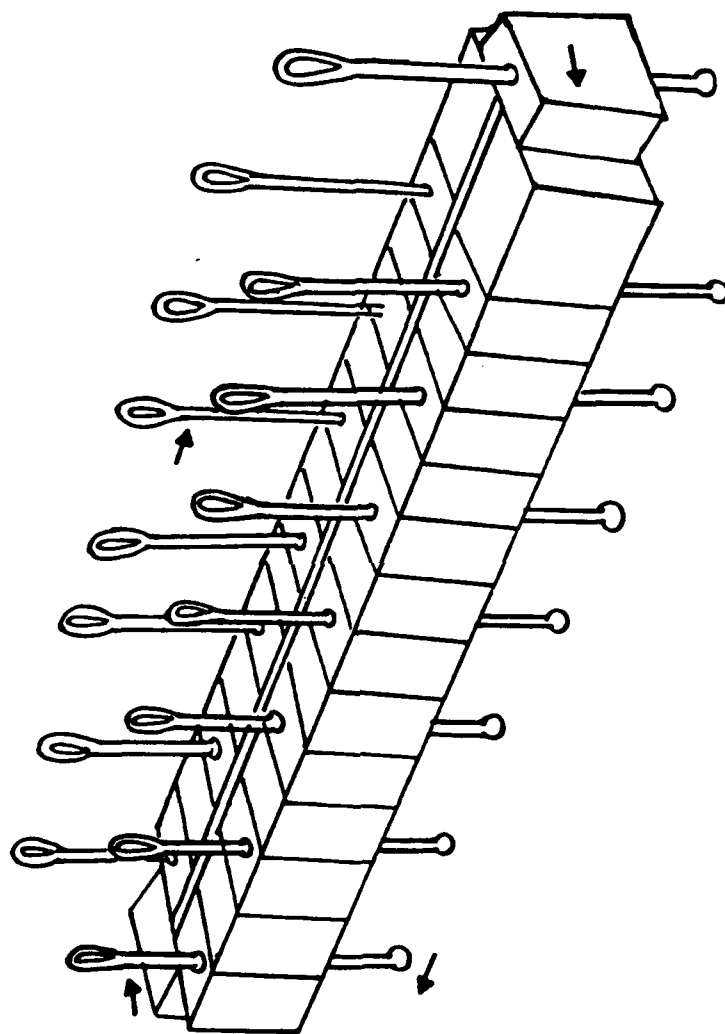


FIGURE 9 - INDIVIDUAL SEQUENTIAL NEEDLE HEDDLES IN CIRCULAR TRACK

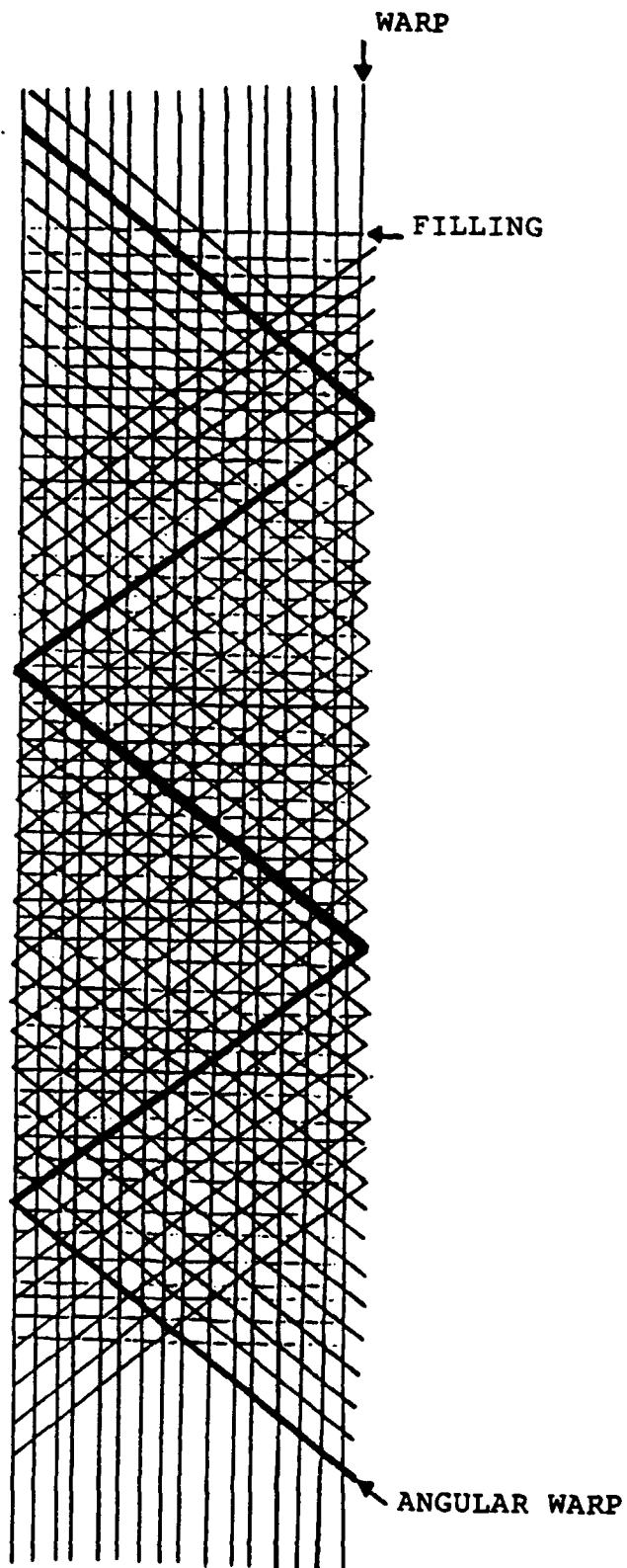


FIGURE 10 - ANGULAR WARP PATTERN INTEGRALLY WOVEN WITH
0 DEGREE AND 90 DEGREE WARP AND FILLING

3.) The needle heddles must move vertically away from the foundation warp sheet for the reed to beat-up the inserted filling into the fell of the foundation fabric, thus binding the angular warp yarns to the foundation fabric.

4.) While the beat-up of the reed is in progress, the needle heddles are away from the base fabric and may index clockwise as programmed.

5.) Repeat steps 1 through 4.

3a. DESIGN CONSIDERATIONS (PRIMARY CONCEPT)

With specific reference to blueprint 01 titled "Proposed idea for Angular Weaving" (side view), it is obvious that one of the greatest design challenges of the proposed machine configuration is that of spatial relationships of mechanical parts. Quite simply, typical textile looms are designed for compact operation.

One type of loom which can be modified to lengthen the reed stroke thus allowing more "mechanics" around the fell of the cloth is the supported shuttle batten loom. It is this type of loom which is depicted in blueprint 01 with batten forward (ghost lines) versus batten rear. Henry Riehl, Incorporated is a major supplier and principal designer of batten looms.

Textile Technologies, Inc. presently performs 80% of all research and development jobs on supported shuttle batten looms. This work includes multi-layer angle interlock, woven tubes, integral woven stiffener concepts, and near-net shape woven parts.

Considerable care must be taken to select needle heddle eyelets tolerant of aerospace fibers. Anytime graphite, for example, is passed through guides, heddles, or a reed, abrasion will occur, damaging some percentage of the fiber bundle. TTI has had years of experience in handling this problem, and is at present weaving 4/10 inch thick angle interlock fabric with minimal fiber degradation, using techniques developed in-house. Knowing what hardware to purchase and applying the right technique will always yield quality fabric.

Blueprint 01 suggests the use of mechanical motions rather than electronics simply due to the concerns arising from the electrical conductivity of graphite. Pneumatic motions may be included as the proposed machine is refined.

Most graphite fabrics are woven from warp yarn packages arranged on a stationary creel. The necessity for the needle heddles to rotate in a clockwise manner requires an approach to compensate for rotation of warp yarns from the creel to the loom. Potential solutions include:

- 1.) Individual warp spools which would rotate with the needle heddles directly.
- 2.) Development of a rotating creel system similar to that used on some Mayer warp knitting machines to prevent entangled warp yarns.

TASK 4: DEVELOP BLUEPRINT OF DESIGN (PRIMARY CONCEPT)

Two blueprints entitled "Proposed Idea for Angular Weaving", blueprint 01 (side view), and blueprint 02 (perspective view) are attached to this report. They are referred to freely in Task 3. Mr. Paul Wagner of Henry Riehl, Incorporated was the draftsman for both drawings.

TASK 5: FORECAST/ASSESS THE CAPABILITY OF THE NEW LOOM DESIGN (PRIMARY CONCEPT)

The proposed primary loom design is fully automated. An automated manufacturing technique for weaving off-axis yarns integrally with perpendicular warp and filling yarns offers financial and structural performance advantages over angle ply lay-ups.

Probable financial advantages stem from the likelihood that fabric formation efficiency should prove to be better than 50% of present efficiency levels for 2-D woven aerospace fabrics while weaving a fabric of twice the thickness (replacing two plies of layed-up 2-D fabric). Additionally, cost savings can be realized in using automated lay-ups with the proposed fabric versus labor intensive angle ply hand lay-ups. Further cost savings may be realized by composite manufacturers in the following areas:

a.) Reductions resulting from warehousing self-contained angular woven frozen prepregs of built-in ply orientations versus warehousing numerous frozen prepregs for angle ply hand lay-ups.

b.) The ability to potentially make thinner and lighter composite parts as a result of improved confidence in the true angle of plies as well as improved damage tolerance.

c.) Quality Assurance check points can conceivably be reduced due to increased accuracy of angular yarns versus angle ply hand lay-ups.

d.) Improvements in damage resistance, thus reducing crack propagation in composite forms will save on future repair costs.

e.) The product form will ideally suited to the production of pultruded composite forms.

No current fiber weaving technology exists which can integrally weave four directions of yarns into a singular woven form. The weaving approach described as the "primary concept" of this report is capable of attaining what presently does not exist. The resultant fabric would have the following specific characteristics:

a.) Evenly spaced and precisely oriented yarn placement is possible in each of the four directions woven.

b.) Zero and ninety degree yarns excluded, the two angular yarns may be oriented within a practical range of 10 to 80 degrees. This is controlled via weave design and needle heddle activation points.

NOTE: Significant reductions in composite weight and thickness may be possible due to more even distribution of angular yarns throughout an angle ply lay-up, thus reducing engineering risk factors. For example, a 60/10/30 woven fabric would allow for angular yarns to be dispersed throughout the full thickness of a lay-up versus a single angular ply in a 10 ply lay-up. The resultant multi-angular fabric would be quasi-isotropic in properties within itself making it a basic building block for producing composite parts. In order to produce a composite that has quasi-isotropic properties and will not distort in fabrication due to unbalanced forces, the engineer need simply use units of the proposed fabric. The composite engineer does not need to go through the process of balancing forces, they would be inherently balanced.

c.) Inherent to the technique is the ability to tailor the amount of 0 degree, 90 degree, and angular yarns woven into a material tailored to a specific application.

d.) Although the angular yarns are subjected to abrasion in the needle heddles, they will not experience abrasion resulting from the beat-up of the reed as is typical in weaving techniques. As a result, the proposed weaving process is not expected to subject the yarns to severe or unusual abrasion. The translational efficiency of fiber physical properties should be no less than those experienced with standard weaving techniques.

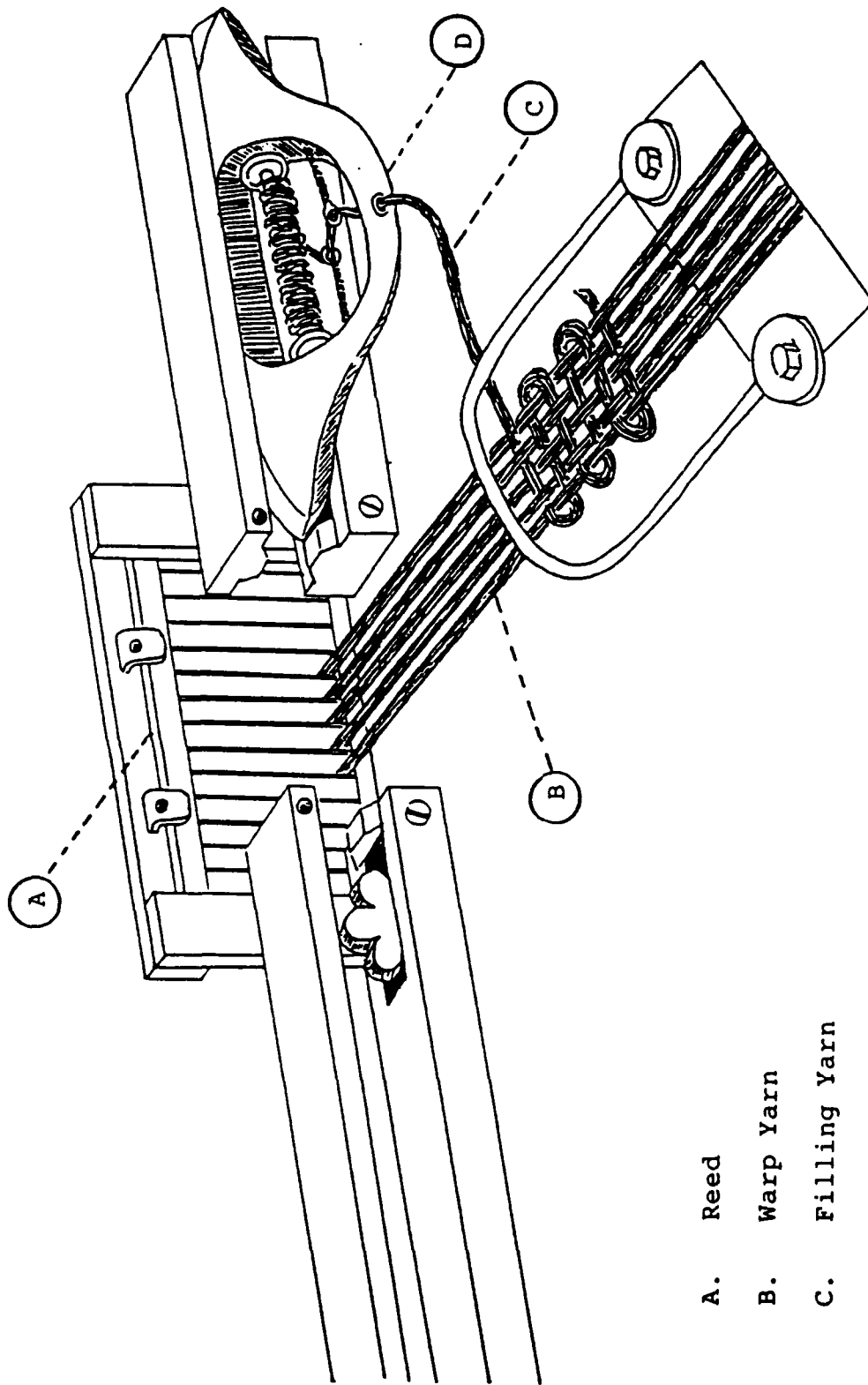
e.) In keeping with the Air Force objective of woven shape and tubular fabric capability, the proposed loom design includes the use of a supported shuttle filling yarn insertion technique (See Figure 11). Filling inserted via a shuttle yields the looped edge (selvage) necessary to weave woven shapes.

NOTE: Every structural shape utilized in aerospace composites requires in-depth textile design analysis to ascertain feasibility of weaving. The proposed weaving technique would be bound by the same guidelines.

f.) Keeping in mind that at present it is considered practical to activate a singular rotating track of needle heddles above the foundation warp and another below the foundation warp, integral multilayer fabric constructions such as those illustrated in Figure 12 A and B would be possible. The fabric construction illustrated in Figure 12C is not presently considered practical. Further refinement of the mechanical details of the proposed loom design may broaden the possibility of fabric design.

IV. CONCLUSION

Structural performance is the foremost consideration of the composite engineer when designing an aerospace component. The composite engineer selects a fiber reinforcement, a matrix and a fiber "architecture" from available materials, to meet specific design parameters.



- A. Reed
- B. Warp Yarn
- C. Filling Yarn
- D. Shuttle

FIGURE 11 - SUPPORTED SHUTTLE FILLING YARN INSERTION TECHNIQUE

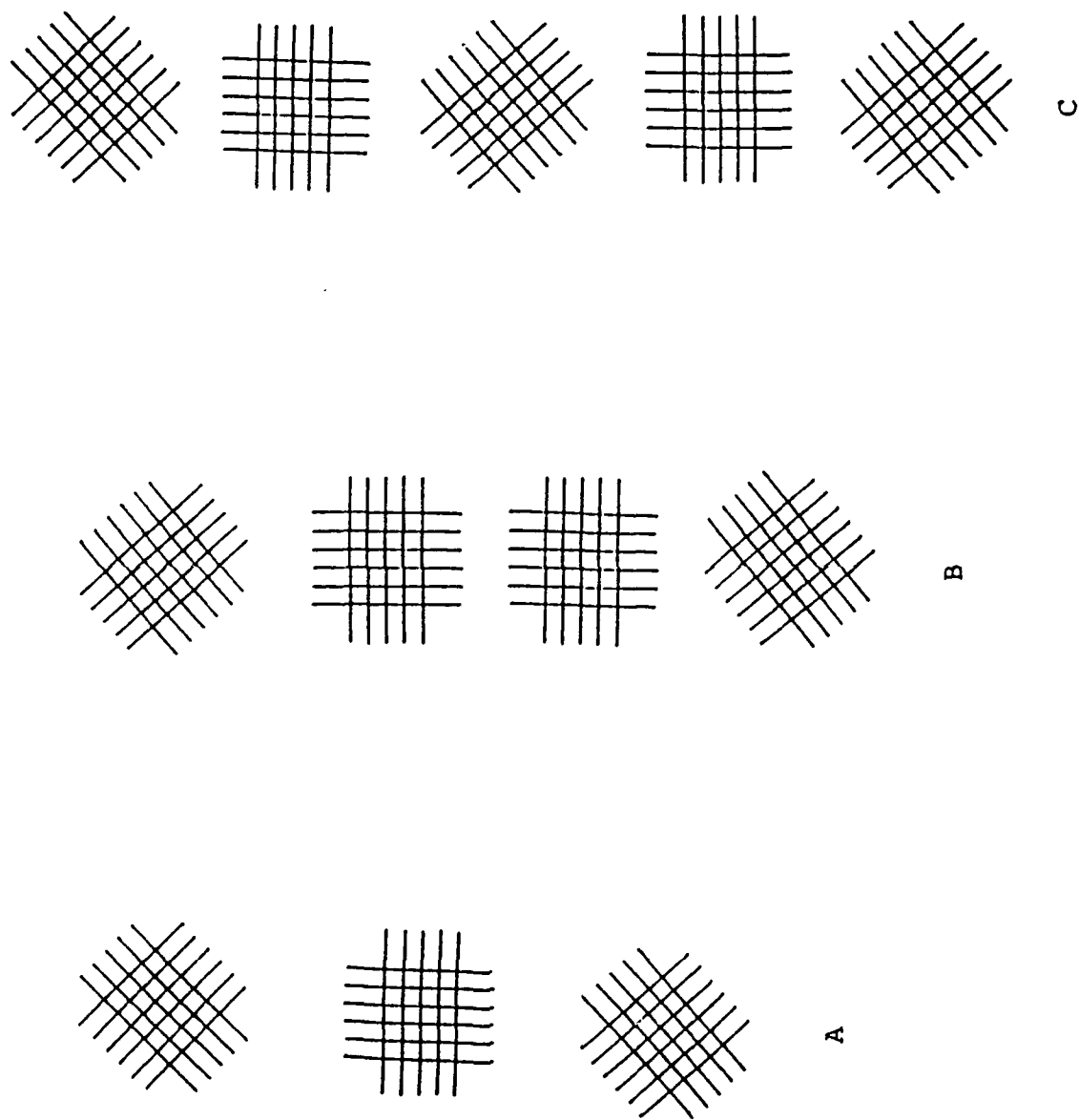


FIGURE 12 - MULTI-ANGULAR MULTI-LAYER FABRIC SCHEMATICS

Fiber "architecture" is defined as the spatial positioning of fibers (i.e. in-plane [0 degrees/90 degrees] and off-axis [± 45 degrees]), relative to a structural composite preform. The ability to place these fibers in specific orientations provides for the tailorability of structural properties of composite materials. The composite engineer relies on the textile engineer to develop fabrication techniques which automatically and accurately place fibers in specific locations. Close cooperation between the composite engineer and the textile engineer facilitates the successful execution of high quality critical components.

Most recently, primarily through the transatmospheric vehicle technology surge sponsored by the Air Force, composite engineers in all fields are being forced to stretch the limits of their technology as well as that of their suppliers. Composite engineers are demanding intricate textile "architectures" for critical parts fabrication. In recent months, this need has resulted in increased interest in angle interlock woven multilayer fabrics and near net shapes as well as other 3-D woven materials. The leading edge of composite weaving technology is moving away from "available" specified material forms to woven forms tailored to specific end-use applications. Angle interlock fabrics offer significant design flexibility in this regard, but find themselves limited in some critical applications due primarily to the absence of angular yarns in the X, Y, and Z configurations.

The capability to introduce integral angular woven yarns into multilayer fabric "architectures", as the proposed primary concept design would do, would significantly impact critical composite structures necessary to meet the ambitious goals set forth by the Air Force to fly an X-30 transatmospheric vehicle in the early 1990's.

Whether the proposed weaving technique is used in aircraft engine components or aircraft primary structures, composite structures can expect to benefit from increased off-axis tensile properties, improved damage tolerance, and increased interlaminar shear strength and rigidity.

V. PHASE II PRELIMINARY PLAN

Phase I of Air Force contract number F33615-87-C-2793 has been successfully completed. The end result of this contract being a plausible design for a textile machine capable of angular weaving to fabricate three-dimensional, multi-layer, multi-angular structural composite preforms.

A potential near-term application of the proposed weaving technique has been identified as integrally woven composite turbine blade preforms presently under development at major aircraft engine manufacturers.

Off axis fiber orientations are desirable in near-net shape woven turbine blade fiber preforms. For aerodynamic reasons, the airfoil portion of a turbine blade is generally twisted from root to tip.

During its functional operation, the airfoil will have the natural tendency to untwist. Integral placement of off-axis fibers would be beneficial on the surface of an airfoil fiber preform to counteract any shear twisting in that region of a woven turbine blade fiber preform.

The loom design/feasibility study undertaken in Phase I offers simply a foundation on which to build a secure technology base, geared toward manufacturing multi-angular woven fabrics for aerospace applications. The task of refining the proposed loom design, specifying specific part dimensions, and construction of a prototype loom is well suited for a Phase II SBIR award.

Textile Technologies, Inc. (TTI) and its principal subcontractor, Henry Riehl, Incorporated are not strangers to textile loom design. In fact, in March 1988, TTI installed a highly specialized jacquard weaving system, designed jointly by TTI and Henry Riehl, Inc., and manufactured by Henry Riehl, Inc. The new loom was funded under NASA Contract No. NAS1-18358, entitled "Development of Advanced Woven Composite Materials and Structural Forms". The weaving apparatus was designed primarily for weaving X, Y, and Z fiber preforms for composite applications, even though the key technology need at NASA is for multi-angular multi-layer woven preforms.

It is only natural that an established aerospace weaver have a hand in designing a loom modification to weave multi-axial fabric and preforms from high modulus yarns.

As stated previously in this report, there has never been a loom specifically designed to weave high modulus yarns. Yet weavers such as Textile Technologies, Inc. do in fact weave high modulus yarns (up to 120 million psi tensile modulus) on looms which are modified according to internally developed specifications.

Phase II of this program is the ideal vehicle for realizing the proposed fabric properties inherent to multiaxial woven fabric manufactured on a loom configured as shown in blueprints 01 and 02, jointly entitled "Proposal Idea for Angular Weaving".

Textile Technologies, Inc. intends to submit a formal proposal to the United States Air Force to contract the same team of Henry Riehl, Inc. and TTI to further refine the proposed machine design and to manufacture a fully automated prototype weaving machine. The machine shall be of sufficient size to weave representative fabric constructions to demonstrate the versatility of the technology, and through composite testing, the true structural advantages of integrally woven multi-axial fabric.

GLOSSARY

- BATTEN LOOM: A loom in which the shuttle is supported all the way across the shed as it inserts a pick.
- BEAT-UP: The actual beating into place of the loose pick that was placed in the shed of the loom during the picking motion. It makes each deposited yarn a component part of the woven cloth. The reed beats the pick into place with each turn of the crankshaft.
- DOBBY HEAD: Mechanical attachment on a loom that controls harnesses to permit the weaving of complex patterns. The limiting factor in the design capability of the dobby head is that the warp ends are in the harnesses and therefore the design may contain only as many distinct movements as there are harnesses.
- FELL OF FABRIC: The few newly woven picks in fabrics which are closest to the reed of the loom.
- FILLING: In a woven fabric, the yarn running from selvage to selvage at right angles to the warp. The filling yarn is carried by a shuttle or other type of yarn carrier.
- FLY SHUTTLE-LOOM: A loom in which the shuttle is actually thrown from one side of the shed to the other.
- GUIDE BARS: A series of eyelets that control the path of a yarn.
- HARNESS: A frame holding the heddles in position in the loom during weaving. Harnesses form the shed of the loom and are raised and lowered in accordance with the pattern.
- HEDDLE: A round steel wire or thin flat steel strip with a loop or eye near the center through which one or more warp threads pass on the loom so that their movement may be controlled in weaving. The heddles are held at both ends by the harness frame.
- JACQUARD HEAD: A mechanical device used in weaving that is highly versatile and allows the production of large intricate designs. The weave pattern is achieved by a series of punched cards. Each card perforation controls the action of one warp thread for the passage of one pick.

GLOSSARY (continued)

- LOOM: The machine used in making woven fabric.
- NEEDLE LOOM: A loom where the picks are inserted by a single curved needle. Two picks are inserted at one time. Generally used for narrow width tapes.
- PATTERN CHAIN: Consists of a pegboard or a punched cylinder of paper or plastic. Each row of holes in the pegboard or cylinder controls a row of the weave pattern, mechanically determining which warp yarns will be raised and which lowered to produce the desired shed.
- PICK: See filling.
- REED: A comb-like device on a loom which spaces the warp yarns and also beats each succeeding filling thread against that already woven. The reed consists of a top and bottom strip of wood or metal into which metal strips or wires are set. The space between two adjacent wires is called a dent, and the warp is drawn through the dents. The fineness of the reed is calculated by the number of dents per inch.
- REED STROKE: The distance the reed moves from the back of the shed to the fell of the cloth to beat-up a pick.
- RIGID RAPIER: A straight rigid device made of metal or a composite material with an attachment on the end to carry the filling yarn through the shed. The rapier inserts the filling yarn from only one side, so it must be withdrawn prior to beat up.
- SELVAGE: The narrow edge of woven fabric that runs parallel to the warp. Usually made with stronger yarns in a tighter construction than the body of the fabric to prevent raveling.
- SHED: A path through and perpendicular to the warp in the loom. The shed is formed by raising some warp threads by means of their harnesses, while others are left down. The shuttle passes through the shed to insert the filling.
- SHUTTLE: A boat-shaped device, usually made of wood with a metal top, that carries filling yarns through the shed in the weaving process. The shuttle holds a quill on which the filling yarn is wound.

GLOSSARY (continued)

- TOW: A large group of continuous filaments without any definite twist.
- WARP: The set of yarn in all woven fabrics that run lengthwise and parallel to the selvage and is interwoven with the filling.
- WARP KNITTING: A type of knitting in which the yarns generally run lengthwise in the fabric. The yarns are prepared as warps on beams with one or more yarns for each needle. The fabric is constructed by interlocking series of loops of one or more yarns.
- WOVEN FABRIC: A fabric composed of two sets of yarns, warp and filling, and formed by interlacing these yarns to form a fabric. The manner in which the two sets are interlaced determines the weave.
- YARN: A generic term for an assemblage of fibers or filaments, either natural or made-made, suitable for knitting, weaving, or otherwise intertwining to form a textile fabric. Yarn may or may not contain twist.